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# How visually impaired cyclists ride regular and pedal electric bicycles



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## ABSTRACT

The present study investigates whether visually impaired cyclists compensate for their vision limitations by maintaining a lower speed or a larger distance to the kerb than normally sighted cyclists when riding a regular bicycle or pedal electric bicycle (pedelec). A normally sighted control group ( $n = 10$ ), a peripheral visual field loss group ( $n = 9$ ), and a low visual acuity group ( $n = 12$ ) rode a fixed route (7.5 km) in the Netherlands on a regular bicycle and on a pedelec. Speed and lateral position were measured when participants cycled a (I) one-way cycle path, (II) two-way cycle path, (III) residential area, and (IV) shared space zone. With regard to both the regular bicycle and the pedelec, no significant speed or lateral position differences were found between the three groups. In conclusion, for some people with severe and permanent visual impairments, and under certain circumstances, regular bicycle and pedelec riding may be possible without noticeable speed reduction or adapted lane position to compensate for their functional impairment. The present findings may further optimise the cycling advice provided by mobility trainers of vision rehabilitation centres and the independent mobility of visually impaired people.

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## 1. Introduction

### 1.1. Cycling with low vision

The popularity of cycling as a regular mode of transport is growing around the world (Pucher & Buehler, 2017). In the Netherlands, 27% of all journeys are made by bicycle (Centraal Bureau voor de Statistiek, 2018; Harms & Kansen, 2018). Independent cycling is important for the social participation of people with permanent vision loss, particularly for those who are not allowed to drive a passenger car. In contrast to driving, for which formal minimal vision requirements exist, there are no vision constraints for cycling in the Netherlands. Visually impaired people are legally allowed to cycle as long as they do not endanger themselves or others (Wegenverkeerswet 1994 artikel 5 [Article 5 of Dutch Road traffic act of 1994], 1994). This emphasis on personal responsibility may leave people with visual impairments who consider (continuing) to cycle, as well as health-care professionals who are asked for advice, in doubt whether, when, or where it is safe to cycle or not. Research into cycling behaviour of visually impaired people is therefore of importance.

Mobility programmes provided by Dutch vision rehabilitation centres focus on optimising the independent mobility while preserving safety. Based on the individual's needs, the mobility trainer provides advice on independent cycling. This

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advice is mainly based on the mobility trainer's expertise and experience, as there is limited evidence-based information about cycling with low vision. Wilhelm and Endres (2004), who conducted a survey in Germany, stated that binocular visual acuity below 0.1 (decimals; Snellen notation: 6/60 or 20/200), a visual field diameter less than 60 degrees, or a central scotoma (i.e. spot with vision loss or blindness) of more than 10 degrees are unconditional contra-indications for cycling. More recently a Dutch study (Jelijs, Heutink, De Waard, Brookhuis, & Melis-Dankers, 2019) showed that the majority (85%) of respondents who did not meet these criteria still cycle on a daily basis. However, there were also respondents with milder vision impairments who had ceased cycling. This indicates that visually impaired cyclists base their personal assessment of cycling safety not solely on their visual function impairment and that the ability to compensate for limitations may also play a role.

Compensation strategies can be described in terms of Michon's (1971, 1979, 1985) hierarchical structure of the road user task. Michon's model divides road user decision-making into three levels: (1) strategic, (2) tactical, and (3) operational. The strategic level refers to making general decisions, such as selecting the route and departure time, predominantly planned before the ride, basically without time-pressure. The tactical level concerns manoeuvring in response to the prevailing situation, such as overtaking others or avoiding obstacles. At this level, cyclists have to make decisions within seconds. Decisions on vehicle control are made at the operational level. These decisions, including steering and braking, are made under high time-pressure (within milliseconds) and are mostly made unconsciously and automatically.

Visually impaired cyclists may experience problems at the operational and tactical levels as these are subjected to time-pressure and derive mainly from (visual) environmental input (Michon, 1985). Overlooking the traffic situation appears to be an important general difficulty for visually impaired cyclists, while other bicycle control difficulties may depend more on the nature of the visual function impairment. For example, cyclists with low visual acuity may have particularly more route-finding difficulties, while cyclists with peripheral vision loss may have more difficulties with choosing the distance to the kerb (Jelijs et al., 2019) or evaluating the line of travel (Connor, 1992).

Cyclists can compensate for difficulties at one of the levels of Michon's (1971, 1979, 1985) model by optimising decisions at the other levels. Similar to cyclists who perform dual tasks (De Waard, Lewis-Evans, Jelijs, Tucha, & Brookhuis, 2014; Kircher, Ahlstrom, Palmqvist, & Adell, 2015), cyclists with difficulties overlooking the traffic situation (operational) may compensate by slowing down (tactical) to create more time to acquire a clear view of the situation (Connor, 1992). Similarly, they could maintain a lane position more towards the centre (tactical) to decrease the likelihood to veer off the road and hit the kerb or end up in the verge. Compensation at the strategic level might include choosing alternative routes that potentially have less busy traffic situations. Better knowledge about how visually impaired cyclists adapt their behaviour to cycle independently would facilitate mobility trainers to optimise their cycling advice.

### 1.2. Low vision pedelec riding

In the near future, cycling popularity will further increase partly because of the advance of pedal electric bicycles (pedelecs) (Pucher & Buehler, 2017), which provide pedal support up to 25 km/h (or 16 mph) (SWOV, 2017). Pedelec riding requires less physical energy than riding a regular bicycle (Sperlich, Zinner, Hébert-Losier, Born, & Holmberg, 2012; Theurel, Theurel, & Lepers, 2012), making it easier to ride longer distances or hilly terrains (Johnson & Rose, 2015; Pucher & Buehler, 2017). In the Netherlands, at present approximately 30% of all newly sold bicycles is a pedelec (Bovag-Rai Mobiliteit, 2018; Confederation of the European Bicycle Industry, 2017). Although the popularity of pedelecs is rapidly increasing among younger people, still most pedelec kilometres are cycled by people aged over 65 (KiM Netherlands Institute for Transport Policy Analysis, 2018). In this age group, where the prevalence of visual impairments increases (Keunen et al., 2011), age-related (sensory function) changes are more likely to pose cycling risks (Kováčsová et al., 2016). An important drawback of pedelec riding is that users are at elevated risk of serious and multiple injuries when involved in a cycling accident (Poos et al., 2017), due to the pedelecs' higher weight and the possibility to cycle faster (Vlakveld et al., 2015).

In the Netherlands, approximately 20 percent of visually impaired and normally sighted cyclists appears to be a frequent pedelec user (Jelijs et al., 2019). Previous studies (e.g., Dozza, Bianchi Piccinini, & Werneke, 2016; Schleinitz, Petzoldt, Franke-Bartholdt, Krems, & Gehlert, 2017) showed that normally sighted cyclists ride pedelecs 2–4 km/h faster than regular bicycles. Faster acceleration and a higher cycling speed may however be more visually demanding as the cyclist has less time to overview the traffic situation. Because of the possible increased safety risks a better insight into the pedelec riding behaviour of visually impaired cyclists is needed.

### 1.3. Aim of the study

To summarise, more information about the cycling behaviour of visually impaired cyclists when they ride a regular bicycle or pedelec is needed to optimise the cycling mobility of visually impaired people. The present experiment aims to provide insight into whether visually impaired cyclists compensate at the tactical level by maintaining (1) a lower cycling speed and (2) a larger distance to the kerb or whether they compensate in another way. Comparisons are made between visually impaired cyclists versus normally sighted cyclists and riding a regular bicycle versus a pedelec to examine potential differences of speed and lane position compensation and cycling safety.

## 2. Method

### 2.1. Participants

Recruitment occurred through media of Dutch vision rehabilitation centres and patient organisations, posters and flyers in rehabilitation centres' waiting rooms, and contacting volunteers who had indicated interest in participating in scientific studies. The recruitment text contained a description of the study and participation requirements. The participants had to be aged 50 years or older and able to ride a bicycle independently in regular traffic. They had to have cycled regularly in the six months before participation. Exclusion criteria were familiarity with the study location, as this would possibly affect speed or lane position and suffering from physical or cognitive issues that affect traffic safety.

A total of 33 volunteers enrolled in the experiment. Two were excluded because they discontinued participation for medical reasons or did not meet the vision selection criteria. The remaining 31 participants were classified into: (1) a normally sighted 'Control' group ( $n = 10$ ), (2) a 'Field' group ( $n = 9$ ) in which peripheral visual field loss was predominant, and (3) an 'Acuity' group ( $n = 12$ ) with low binocular visual acuity ( $BVA \leq 0.25$  decimals; Snellen notation: 6/24 or 20/80) without peripheral field loss. This grouping was based on the results of a visual function assessment, which was conducted on the day of the experiment by a low vision specialist. Binocular visual acuity, visual field, and contrast sensitivity were measured while the participants wore their own prescription glasses or lenses. Visual acuity was measured with the Early Treatment of Diabetic Retinopathy Study test (ETDRS 2000) (Ferris, Kasso, Bresnick, & Bailey, 1982) at 500 lux. The visual field was measured with a Humphrey 30–2 threshold test and an Esterman visual field test. Similar to Cordes et al. (2017), the 20–60 degrees of the visual fields were converted into a visual field score using an overlay grid (Colenbrander et al., 1999; Colenbrander, 2001). Contrast sensitivity was measured with the Vistech Sine Wave Contrast test (Ginsburg, 1984).

The ocular pathologies that were most frequently reported were: glaucoma ( $n = 6$ ), macular degeneration ( $n = 6$ ), achromatopsia ( $n = 3$ ), and nystagmus ( $n = 3$ ). The binocular visual acuity (BVA) in the Acuity group varied from 0.03 to 0.25. Two participants in the Field group had a BVA below 0.25 (0.1 and 0.12).

Table 1 shows participant characteristics per group. There were no significant differences between the groups regarding age ( $\chi^2(2) = 5.173, p = .075$ ), gender ( $p = .902$ , Fisher's exact test), estimated weekly cycling distance ( $\chi^2(2) = 0.223, p = .895$ ), and pedelec experience ( $p = .27$ , Fisher's exact test). Participants indicated the basis on which they cycle (daily, weekly, or monthly) in the summer (May–October) and winter (November–April). Table 1 shows that, in each group, the majority of participants cycles on a daily basis in both summer and winter. The study was approved by the Ethical Committee Psychology of the University of Groningen and performed in accordance with the latest version of the Declaration of Helsinki with regard to ethical standards of research involving human subjects. The participants received a financial compensation for their participation.

### 2.2. Route

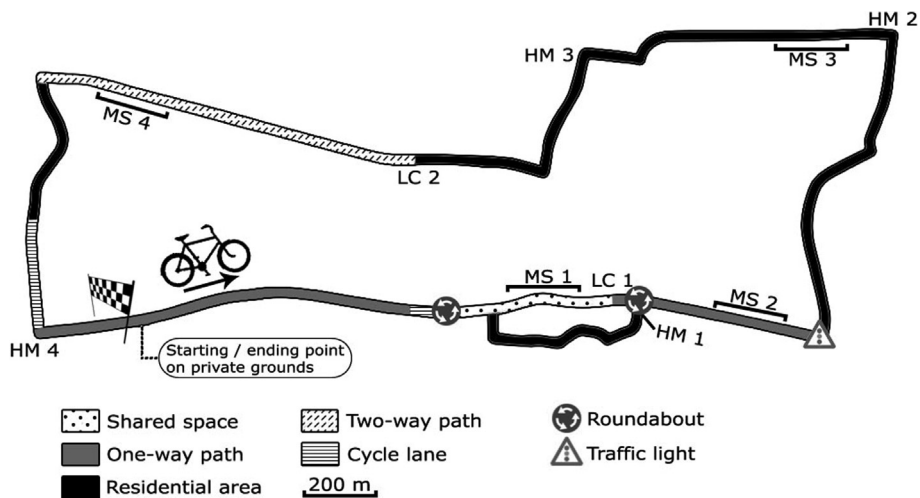
The participants cycled a route (7.5 km) through regular traffic in Haren, a small town (~20,000 inhabitants) close to the city of Groningen in the Netherlands. The starting and ending point of the route was located at private grounds of a vision rehabilitation centre of Royal Dutch Visio. Fig. 1 shows that the route included road types that varied in complexity: dedicated one-way and two-way cycle paths, residential areas, and a shared space zone. In shared space zones the various traffic modalities (pedestrians, cyclists and motorised traffic) are deliberately not separated by the design of the infrastructure. Conventional structures, such as road signs, traffic lights, level differences or road markings are scarce (Havik, Melis-Dankers, Steyvers, & Kooijman, 2012). The route started with a dedicated one-way cycle path (600 m) which did not require

**Table 1**

Age, gender, vision impairment onset, hearing complaints, estimated weekly cycling distance, pedelec experience, and cycling frequency per group.

	Control ( $n = 10$ )	Field ( $n = 9$ )	Acuity ( $n = 12$ )	Total ( $N = 31$ )
Median age [Q1–Q3]	65 [62–73]	63 [53–64]	65 [57–73]	64 [61–67]
Gender, male/female %	50/50	44/56	58/42	52/48
Onset visual function impairment %				
Congenital	–	33	50	–
>10 years ago	–	44	42	–
1–10 years ago	–	11	–	–
Unknown	–	11	8	–
Hearing complaints during cycling %	0.0	22 <sup>a</sup>	8	10
Median weekly cycling distance in km [Q1–Q3]	35 [28–50]	30 [10–63]	35 [20–58]	35 [20–60]
Pedelec experience, yes/no %	40/60	67/33	75/25	61/39
Rides bicycle...				
...daily, summer/winter %	80/70	67/56	75/67	74/64
...weekly, summer/winter %	20/30	22/22	25/25	23/26
...monthly, summer/winter %	–/–	11/22	–/8	3/10

<sup>a</sup> One participant in this group did not answer the corresponding question.



**Fig. 1.** Schematic overview of the route's road types, speed and lateral position measurement segments (MS), lane changes (LC), and head movements rating locations (HM).

difficult manoeuvring and enabled the participants to become accustomed to the bicycles. Thereafter, more complex manoeuvres followed, including turning left at controlled or uncontrolled crossings, taking roundabouts, crossing the town's main road, anticipating two abrupt changes of the cycle road's trajectory (see [Appendix A](#)), and cycling through the town's centre shared space zone twice per ride.

### 2.3. Materials

The regular bicycle (Batavus San Remo 2016) and the pedelec (centre-engine, Batavus Stream 2016) were city bicycles with a similar geometry and seating position (see [Fig. 2](#)). The bicycles were equipped with mirrors to enable people to participate who normally use mirrors. The instructor rode behind the participant on a Sparta ION RX + pedelec.

Two Contour + 2 GPS, 170° widescreen lens, action cameras were mounted on the right-hand side of the handlebar and handlebar stem (see [Fig. 2](#)). One camera was directed towards the front providing a broad overview of the traffic situation. The other was directed downwards to the front wheel axis. The handlebar of the instructor bicycle was instrumented with another Contour + 2 camera, directed towards the front, to capture a broader overview of the traffic situation and the participants' head movements. The instructor gave spoken protocolled route instructions via Cobra MT615 walkie-talkies, which the instructor and the participant wore around their neck.

### 2.4. Procedure

The experiment was conducted between June and October 2016. The participants received by mail a written confirmation that included a general overview of the study, the instruction to bring their usual cycling aids, and a questionnaire based on [Westerhuis and De Waard \(2014a\)](#), containing 28 general questions about the participant's characteristics: demographics, bicycle use and experience, the visual function impairment, and other physical and cognitive limitations.



**Fig. 2.** The regular bicycle (left), the pedelec (centre), and the position of the GPS action cameras (right).



Three researchers carried out the experiment, two of which were present during each experimental session with the role of either instructor or assistant. The instructor used a protocolled script to give equal, spoken instructions to each participant. The assistant's role included setting up the bicycles and cameras. One experimental session, without the visual assessment, took approximately three hours. In case of adverse weather conditions the experimental session was postponed to a later date.

The instructor informed the participant about the structure of the session and answered questions that participants had before cycling the route. After the participant had given written informed consent the participant carried out a number of tasks on the pedelec, including riding a short course on the car park, emergency braking, and performing a cone slalom task. These tasks enabled the participant to accustom to the bicycles. At the same time, the instructor ascertained that the participant understood the instructions via the walkie talkie and estimated whether riding through regular traffic would be safe.

Each participant cycled the route (Fig. 1) on the regular bicycle and the pedelec in counterbalanced order. They were instructed to cycle the way they usually do, to not talk back via the walkie talkie, and to contact the instructor only if necessary. The instructor's following distance varied based on the prevailing circumstances. For example, the distance was large (10–15 m) at straight route sections to comfort the participant, while the distance was smaller (1–2 m) before busy crossings to be able to keep up with the participant. The instructor read aloud through the walkie talkie the route-instructions from a clipboard attached to the instructor's bicycle.

After both rides a structured interview was taken, which included questions about any irregular or difficult situations that the participant experienced during that ride. A number of additional questions were asked after the second ride, for example about the resemblance between the bicycles, use of the bicycle mirrors, and familiarity with the route. The visual assessment of the visually impaired participants took place at the end of the session.

## 2.5. Analysis

### 2.5.1. Speed and lateral position

Speed and lateral position were measured at four 200-metres segments (Fig. 1, MS) that varied in complexity: (I) a one-way dedicated cycle path of 2.2 m wide, (II) a two-way dedicated cycle path of 2.8 m wide, (III) a residential area of 6.2 m wide, and (IV) a shared space zone of 5.6 m wide (see Fig. 3). Fig. 1 shows that the participants cycled through the shared space zone twice per ride. Because this measurement segment was situated relatively early in the route, and the participant had possibly not become accustomed to the bicycle yet, speed and lateral position of the second time in the shared space zone were measured.

The videos were analysed using the software programme Kinovea 0.8.24 and Contour Storyteller 3.6.2.1043 for Windows. Based on the GPS location the cameras registered cycling speed at the measurement segments (Fig. 1) twice per second.



**Fig. 3.** The speed and lateral position measurement segments (MS) from the participants' perspective: (I) the one-way cycle path, (II) the two-way cycle path, (III) the residential area, and (IV) the shared space zone.

Samples where the speed was affected by other traffic (e.g. traffic jams or overtaking manoeuvres) were excluded, after which the mean cycling speed was calculated per segment.

The lateral position was measured at 15 fixed locations within each measurement segment (Fig. 1) by overlaying a perspective grid on the video using Kinovea (see Westerhuis, Jelijs, Fuermaier, & De Waard, 2017). By using a measurement tool (see Westerhuis & De Waard, 2016), the perspective grid represented the absolute dimensions in front of the bicycle's front wheel (Fig. 4). The mean lateral position per segment was calculated after excluding samples in which the lateral position was affected, for example by stationary traffic, rubbish or puddles on the road.

### 2.5.2. Head movements and lane changes

Overviewing the traffic situation and anticipating to the road trajectory belong to the most important bicycle control difficulties of visually impaired people (Jelijs et al., 2019). To gain insight into this, (1) the quality of the participants' head movements and (2) their ability to anticipate correctly to deviating road trajectories were registered.

Using the camera recordings from the instructor bicycle the researcher rated the participant's head movements 'sufficient', 'insufficient', or 'not sure' during the first encounter of four difficult locations. Based on the interviews after the first rides and Jelijs et al. (2019), these locations were: an intersection between a motorised-traffic road and a dedicated bicycle lane adjacent to a roundabout (HM 1; see Fig. 1), a left turn at a cross road (HM 2), a left turn into a side street (HM 3), and an intersection with the town's main road (HM 4). The researcher's rating was based on whether the participants turned their head to both the left and right at least once. The left turn ratings also depended on whether the participants looked over their shoulder.

The route contained two lane changes (Fig. 1, LC) where the participant had to move to a mandatory cycle path that deviated from the prevailing road trajectory (see Appendix A). Participants did not receive any route-instructions when approaching these lane changes, but after missing a lane change the instructor guided them to the mandatory bicycle path. The researcher registered during the video-analysis whether the participant moved to the mandatory cycle paths at the first encounter.

### 2.5.3. Statistical analysis

Because the data were not normally distributed, non-parametric tests were performed to analyse effects of speed, lateral position, head movements, and lane changes. The mean speeds per segment were converted into an average cycling speed of the whole ride per bicycle to increase statistical power. The lateral positions were compared per measurement segment as the road width may affect lateral position (Greibe & Buch, 2016). Kruskal-Wallis tests were performed to compare the groups' average cycling speed and lateral position measurements. Within-group speed comparisons were made using Wilcoxon signed-rank tests to explore (1) if the participants rode faster on a pedelec than on a regular bicycle and (2) the speed effects of route familiarity by comparing the first versus the second ride. Spearman's rho ( $r_s$ ) and biserial ( $r_b$ ) correlations were calculated to study the relationships between cycling speed versus the severity of the visual function impairments, age, and pedelec experience. The categorical variables, i.e. the head movements and anticipating correctly to the lane changes were analysed using two-tailed Fisher's exact test (FET). The significance level was set to  $\alpha = 0.05$ . Effect sizes were calculated using Pearson's  $r$ , where 0.5 is considered a large effect, 0.3 a medium effect, and 0.1 a small effect (Fritz, Morris, & Richler, 2012). All data were analysed using IBM SPSS Statistics 23 and Microsoft Excel 2010 for Windows.



**Fig. 4.** Lateral position measurement by overlaying a perspective grid (white) on the video using Kinovea. The perspective grid represented the absolute dimensions (300 × 30 cm) in front of the bicycle's front wheel.

### 3. Results

#### 3.1. Speed

##### 3.1.1. Regular bicycle

The average speed of the whole ride on the regular bicycle did not differ significantly between the Control group, the Field group, and the Acuity group ( $H(2) = 0.61, p = .738$ ). Fig. 5 shows that the average speed varied from 16.7 to 17.3 km/h. Compared to the Control group, relatively large standard deviations were measured in both the Field and Acuity groups. This indicates that the speed variability between participants in these groups was higher compared to the Control group.

##### 3.1.2. Pedelec

There was no significant difference between the three groups regarding the average speed of the whole pedelec ride ( $H(2) = 2.33, p = .312$ ). Fig. 5 shows that the average speed of the groups varied from 17.6 to 19.1 km/h. Compared to the Control group, relatively large average speed variabilities were measured within both vision impairment groups. Appendix B presents a full overview of the mean speeds per bicycle and measurement segment.

##### 3.1.3. Within-groups speed results

Within the Control group and the Field group a significantly higher average speed was measured on the pedelec than on the regular bicycle. On average the Control group cycled 2.1 km/h faster on the pedelec than on the regular bicycle ( $z = -2.803, p = .005, r = -0.63$ ) and the Field group maintained a 1.5 km/h higher average speed ( $z = -2.666, p = .008, r = -0.63$ ). In the Field group, no significant relationships were found between the average speed on the regular bicycle and field loss severity ( $r_s = -0.345, p = .364$ ) or age ( $r_s = 0.492, p = .179$ ). With regard to the Field group's average speed on the pedelec, no relationships were found with the field loss severity ( $r_s = -0.227, p = .557$ ) or age ( $r_s = 0.644, p = .061$ ) as well as with pedelec experience ( $r_b = 0.170, p = .968$ ).

The Acuity group did not ride significantly faster during the pedelec ride ( $z = -1.647, p = .099, r = -0.34$ ). In fact, three low acuity participants, with visual acuity varying from 0.13 (decimals; Snellen notation: 6/48 or 20/160) to 0.03 (6/240 or 20/800), cycled 0.8 to 2.1 km/h slower during the pedelec ride than the regular bicycle ride. These participants reported having no pedelec experience, two of which indicated in the pedelec ride interview that they limited their speed deliberately, because they were (1) not used to the bicycle's fast response time or (2) afraid of losing the overview of the traffic situation. There was no significant relationship between the average speed on the regular bicycle and visual acuity ( $r_s = 0.325, p = .303$ ) or age ( $r_s = -0.435, p = .157$ ). Furthermore, there was no significant relationship between the average speed on the pedelec and visual acuity ( $r_s = 0.550, p = .064$ ) or pedelec experience ( $r_b = 0.451, p = .920$ ). This is also illustrated by a participant with a visual acuity of 0.12 (6/50 or 20/170) without pedelec experience who rode the pedelec 3.4 km/h faster than the regular bicycle, which was the largest difference among all visually impaired participants. Within the Acuity group a strong negative correlation was found between age and the average cycling speed during the pedelec ride ( $r_s = -0.582, p = .047$ ): as age increased, the cycling speed on the pedelec decreased.

There was no significant difference between the average speed of ride 1 versus ride 2 in either the Control group ( $z = -1.172, p = .241, r = -0.26$ ), the Field group ( $z = -0.652, p = .515, r = -0.15$ ), and the Acuity group ( $z = -0.08, p = .937, r = -0.02$ ).

#### 3.2. Lateral position

##### 3.2.1. Regular bicycle

The lateral position on the regular bicycle did not differ significantly across the three groups on the one-way path ( $H(2) = 3.93, p = .140$ ), on the two-way path ( $H(2) = 0.51, p = .774$ ), in the residential area ( $H(2) = 1.61, p = .447$ ), and in the shared space ( $H(2) = 0.29, p = .867$ ). Fig. 6 shows the mean lateral positions per measurement segment and group. The standard deviations of the mean lateral position were larger in the Field and the Acuity group than in the Control group on the one-way path, on the two-way path, and in the residential area.

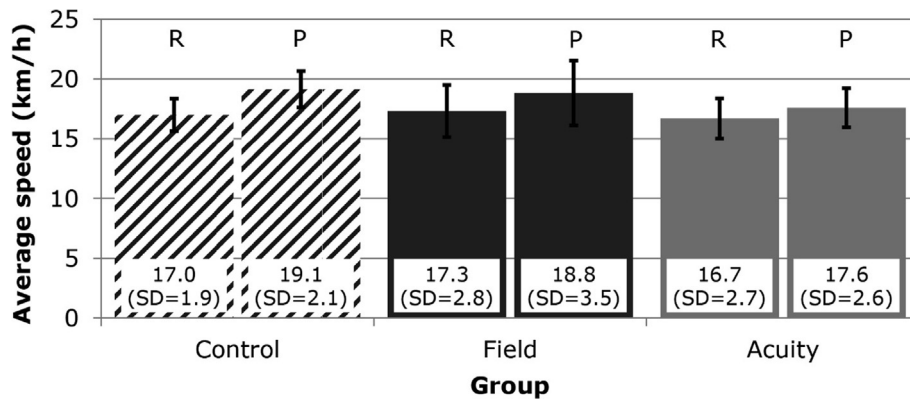
##### 3.2.2. Pedelec

There were no significant group differences of lateral position on the pedelec on the one-way path ( $H(2) = 3.51, p = .173$ ), on the two-way path ( $H(2) = 0.13, p = .937$ ), in the residential area ( $H(2) = 1.30, p = .522$ ), and in the shared space ( $H(2) = 3.66, p = .160$ ). Fig. 7 shows that the variability of the mean lateral position was larger in both vision impairment groups on the one-way path, in the residential area, and on the two-way path.

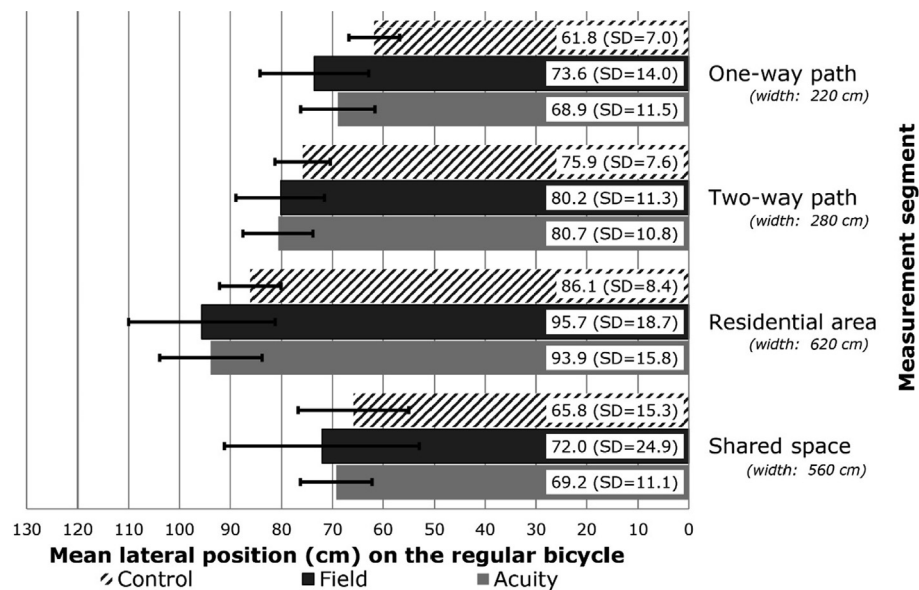
#### 3.3. Head movements and lane changes

Table 2 shows that the participants' head movements at the first encounter of the four locations were rated as 'sufficient' in almost all cases. There were no significant head movements differences between the groups at the roundabout ( $n = 31$ ,





**Fig. 5.** Average speed (km/h) of the whole ride on the regular bicycle (R) and the pedelec (P) per group. The error bars represent the 95% confidence interval.

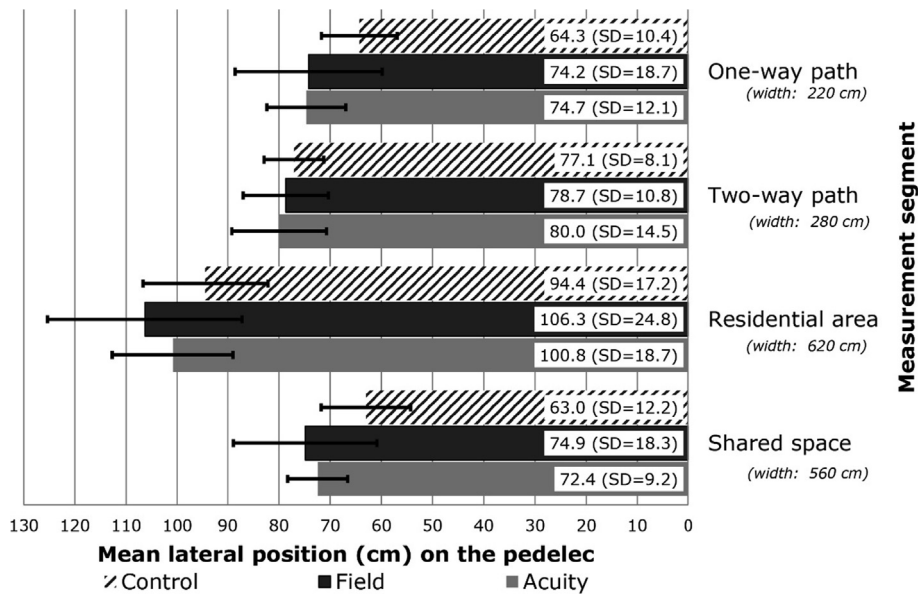


**Fig. 6.** Mean lateral position (cm) on the regular bicycle per measurement segment. The road widths of the measurement segments are shown in the y-axis labels. The kerb is represented by 0. The error bars represent the 95% confidence interval.

$p > .999$ , FET), the first left turn ( $n = 31$ ,  $p > .999$ , FET), and the second left turn ( $n = 30$ ,  $p = .083$ , FET). The participants' head movements at the intersection with the main road were all rated 'sufficient' ( $n = 30$ ).

There was a significant difference between the groups regarding missing the first lane change (LC 1;  $p = .007$ , FET). In total, five participants (16%) missed this lane change during the first encounter. All of these participants belonged to the low visual acuity group. The second lane change (LC 2) was missed during the first encounter by nine participants (29%): two (22%) of them were normally sighted controls, three (33%) belonged to the Field group, and four (44%) to the Acuity group. There was no significant difference between the groups regarding missing the second lane change ( $p = .784$ , FET).

During the entire experiment no accidents occurred and none of the experimental sessions were aborted for safety reasons. Apart from the interventions after participants missed a lane change, the instructor intervened twice: one participant violated a red traffic light and another participant did not give right-of-way to an oncoming car while passing a stationary bus. After video inspection of these participants, who both belonged to the Acuity group, we noticed that their individual lateral position scores deviated strongly from the group mean on almost each measurement segment. Notably, compared to the Acuity group mean, one of them maintained a lateral position closer to the kerb, while the other cycled further away from the kerb. Their mean deviations from all Acuity group's lateral position measurements were  $-9.6$  and  $18.5$  cm, respectively.



**Fig. 7.** Mean lateral position (cm) on the pederlec per measurement segment. The road widths of the measurement segments are shown in the y-axis labels. The kerb is represented by 0. The error bars represent the 95% confidence interval.

**Table 2**

The ratings of the participants' head movements during the first encounter of four locations.

Location	Group	Rating % (n)		
		Sufficient	Not sure	Insufficient
Roundabout	Control	90 (9)	10 (1)	0 (0)
	Field	100 (9)	0 (0)	0 (0)
	Acuity	84 (10)	8 (1)	8 (1)
Left turn 1	Control	90 (9)	0 (0)	10 (1)
	Field	89 (8)	0 (0)	11 (1)
	Acuity	92 (11)	0 (0)	8 (1)
Left turn 2	Control	100 (10)	0 (0)	0 (0)
	Field	78 (7)	0 (0)	22 (2)
	Acuity <sup>a</sup>	100 (11)	0 (0)	0 (0)
Main road	Control <sup>a</sup>	100 (9)	0 (0)	0 (0)
	Field	100 (9)	0 (0)	0 (0)
	Acuity	100 (12)	0 (0)	0 (0)

<sup>a</sup> One missing value in this group.

## 4. Discussion

### 4.1. Speed and lateral position

Cyclists in the low visual acuity and the peripheral visual field loss groups cycled without noticeable reduced speed or adapted lateral position. Contrary to our expectations, at group level, they did not maintain a lower speed or a larger distance to the kerb than the normally sighted cyclists. Nevertheless, the instructors never considered to abort any of the experimental sessions for traffic safety reasons, indicating that all participants showed safe cycling behaviour.

It is possible that there was no need for participants in the visually impaired groups to adapt their speed or lateral position at the present measurement segments, which were straight roads without intersections. The straightness of the measurement segments may also explain why on average participants in the normally sighted and the peripheral field loss groups rode faster on the pederlec than on the regular bicycle, whereas participants in the low acuity group did not. When riding on straight continuous roads information in the peripheral visual field may be of minor importance as the most relevant information is situated in the cyclists' central visual field. Cyclists with low visual acuity would particularly increase the likelihood of missing relevant details when maintaining a higher speed at straight roads.

#### 4.2. Head movements and lane changes

In almost all cases, the participants' head movements were rated 'sufficient', indicating they perceived all relevant objects and approached the corresponding situations with sufficient caution. The first lane change was missed more frequently by the low visual acuity cyclists. A possible explanation is that this lane change demanded more from the central than the peripheral visual field: the cycle path and the corresponding sign were situated adjacent to the road and the path was not introduced by road surface markings. Furthermore, the peripheral field loss cyclists may have used visual scanning strategies and, consequently, did detect this cycle path or sign.

#### 4.3. Implications for vision rehabilitation

There are people with severe permanent low visual acuity or peripheral field loss who are able to cycle independently. The present study does not indicate that imposing more stringent rules or restricting all visually impaired people from riding regular bicycles or pedelecs are necessary. This is in line with a notion that, similar to advice about driving passenger cars (Brouwer & Ponds, 1994) or mobility scooters (Cordes et al., 2017), cycling advice towards visually impaired people should be based on the individual's needs and ability to compensate for shortcomings rather than solely on vision standards.

The present findings suggest that visually impaired cyclists do not by definition maintain a lower speed or larger lateral position than normally sighted cyclists when riding straight road segments. Future studies could focus on circumstances that are more complex, such as in urban areas or when crossing intersections. It is also unclear to which extent the findings apply to different lighting or weather conditions because the present experimental sessions took place in daytime and good weather conditions only.

There may be visually impaired people who cycle but are unaware of speed or lateral position adaptation strategies. Regarding pedelec riding, people with low visual acuity may specifically benefit from maintaining a conservative speed as they did not ride the pedelec faster than the regular bicycle. This may particularly apply to people with a higher age, considering the negative correlation between age and pedelec riding speed that was found in this group. No relationships were found between cycling speed and the severity of the visual function limitation or having pedelec experience. This indicates that people with severe visual function impairments do not necessarily maintain a more conservative cycling speed than those with relatively mild impairments.

Although the first lane change was missed by low visual acuity cyclists only, there were also normally sighted cyclists who missed the second lane change. Such errors can therefore not by definition be attributed to visual function impairments. The participants involved in the traffic light violation and the omission to give right-of-way appeared to maintain lateral positions deviating strongly from the rest of the group. Future studies may investigate whether extreme lateral positions can be seen as potential indicators for unsafe cycling behaviour of visually impaired cyclists.

As the participants cycled regularly before participation and because there were no interventions causing the instructor to abort any experimental session, it is concluded that the participants were able to cycle safely on this particular course, during daytime and in favourable weather conditions. However, general cycling safety is subjected to many factors (Schepers, Hagenzieker, Methorst, Van Wee, & Wegman, 2014) that could not be studied in detail. For example, Prati, Marín Puchades, De Angelis, Fraboni, and Pietrantonio (2018) found that road user behaviour (e.g., violating rules or coping with others' unexpected behaviour) as well as infrastructure characteristics (e.g., intersection types or infrastructure quality) play an important role in collisions between cyclists and motorised vehicles.

The present study provides only limited insight into the participants' daily road user behaviour. Participants were possibly more alert and obedient to traffic rules as they were aware of instructor's presence and no critical instances occurred where participants had to anticipate other road users' unexpected behaviour. Future studies could provide a better insight into the road user behaviour of visually impaired cyclists by examining errors, traffic violations, and critical manoeuvres in more naturalistic settings. At the same time these studies might provide insight into visually impaired cyclists' strategic compensatory behaviour (Michon, 1971; Michon, 1979; Michon, 1985), such as route-planning decisions or avoiding rush hour cycling.

#### 4.4. Study strengths and limitations

To the best of our knowledge, the present study is the first on-road experiment focussing primarily on visually impaired persons' cycling behaviour in regular traffic. It provides a primary insight into their cycling speed and lateral position behaviour while riding a varied route on a regular bicycle and a pedelec.

There are a number of sample-related study limitations. First, it has to be noted that there may be a sampling bias as the participants had to be willing to cycle 15 km in an unfamiliar environment: they were possibly more self-confident or physically fit and, consequently, may have fewer cycling problems and behave safer compared to those who did not sign up. The participation criteria were mentioned in the recruitment text and, therefore, no information is available about the characteristics of those who did not sign up for not meeting the selection criteria. One person signed up but eventually refrained from participation. This person was used to riding a pedelec and, due to medical reasons, unconfident about riding the route on a regular bicycle.

Although the present study included the largest selection of visually impaired people ever studied in an on-road cycling experiment, the groups were too small to perform meaningful additional detailed statistical analyses. The group comparisons should be interpreted with caution because there was some overlap across the groups regarding the visual function impairments. This applies especially to the Field group, which contained two participants who also had a visual acuity below 0.25 (decimals; Snellen notation: 6/24 or 20/80).

The characteristics of the (cycling) infrastructure play an important role for visually impaired cyclists (Jelijs, Heutink, De Waard, Brookhuis, & Melis-Dankers, 2018). For example, the availability of dedicated bicycle paths (Hull & O'Holleran, 2014; Prati et al., 2018; Schepers, Twisk, Fishman, Fyhri, & Jensen, 2017) as well as edge markings and well-detectable bollards (Fabriek, De Waard, & Schepers, 2012; Schepers & Den Brinker, 2011; Westerhuis & De Waard, 2014b) may particularly improve the cycling accessibility for visually impaired people. None of the present measurement segments contained road edge markings and on three segments the road was shared with cars or oncoming cyclists, making the present results applicable to various infrastructural settings. It is, however, unclear to which extent the present findings are generalizable to countries with a different cycling culture. In the Netherlands the majority of the people learn to cycle at primary school age (e.g. Dessing, De Vries, Graham, & Pierik, 2014; Van Goeverden & De Boer, 2013). Visually impaired cyclists from countries where cycling is less common may experience other difficulties and behave differently.

Inherent to performing on-road experiments the circumstances varied between the rides, which possibly affected speed or lateral position. Although data collection took place during summer time, there were differences in weather and lighting circumstances. For example, a number of participants were discomforted by shadows on the road surface or sunlight flickering through the trees. There were also traffic density differences as the sessions took place at varying times of the day and a number took place during school holidays. Furthermore, a drawback of using GPS to determine speed on a fixed segment is that the faster participants' speed measurements are based on fewer GPS-samples, which makes them less reliable than those of the slower cyclists. In addition, it cannot be ruled out that the instructor, who followed the participants, has had an influence on the cycling speed of the participants.

#### 4.5. Conclusion

The present study indicates that cyclists with low visual acuity or peripheral visual field loss, at group level, do not cycle with a noticeable different speed or lateral position than normally sighted cyclists. On average, the visually impaired groups did not compensate at various straight road segments by maintaining a lower speed or a larger distance to the kerb. Nevertheless, they completed a varying route, during daytime and in favourable weather conditions, by riding a regular bicycle or pedelec in a safe manner. This indicates that there is no need to introduce legislative restrictions limiting the regular bicycle or pedelec use of visually impaired people. Future studies could focus on how visually impaired cyclists behave in their daily life and in other circumstances, for example in more urban areas and in less favourable weather conditions.

#### CRedit authorship contribution statement

**Bart Jelijs:** Conceptualization, Methodology, Formal analysis, Investigation, Resources, Writing - original draft, Writing - review & editing, Project administration. **Joost Heutink:** Conceptualization, Methodology, Resources, Writing - original draft, Writing - review & editing, Supervision, Project administration, Funding acquisition. **Dick de Waard:** Conceptualization, Methodology, Resources, Writing - original draft, Writing - review & editing, Supervision, Project administration, Funding acquisition. **Karel A. Brookhuis:** Conceptualization, Methodology, Writing - original draft, Writing - review & editing, Supervision, Funding acquisition. **Bart J.M. Melis-Dankers:** Conceptualization, Methodology, Resources, Writing - original draft, Writing - review & editing, Supervision, Project administration, Funding acquisition.

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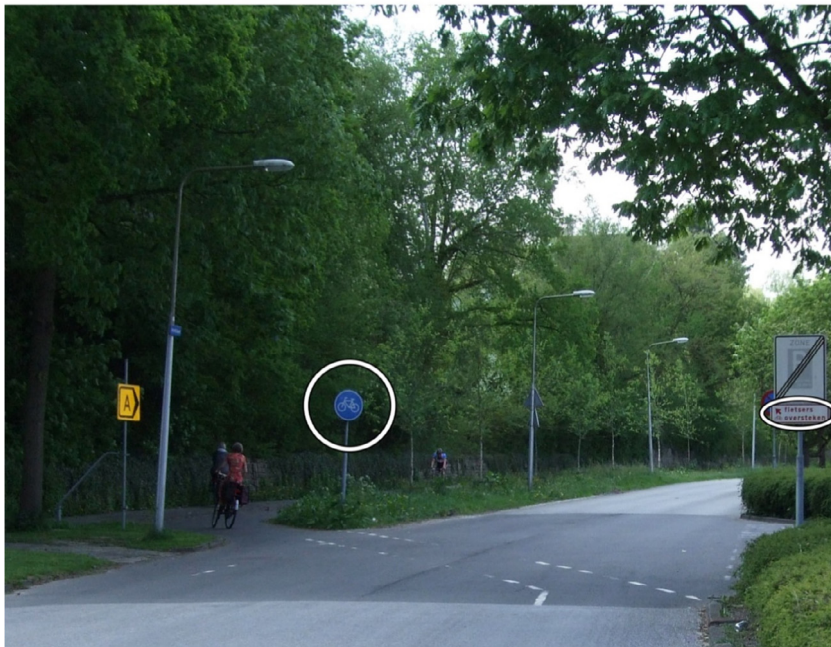
We thank all participants for their cooperation. We thank Frank Westerhuis for his assistance during the setup of the study, Robbert Brouwer and Esther Meijer for their assistance during data collection, Nadine Naumann and Karin Bosker for executing the visual function assessments, and Mr. Hilarides for his advice on selecting the bicycles. Furthermore, we thank the reviewers for their helpful suggestions.

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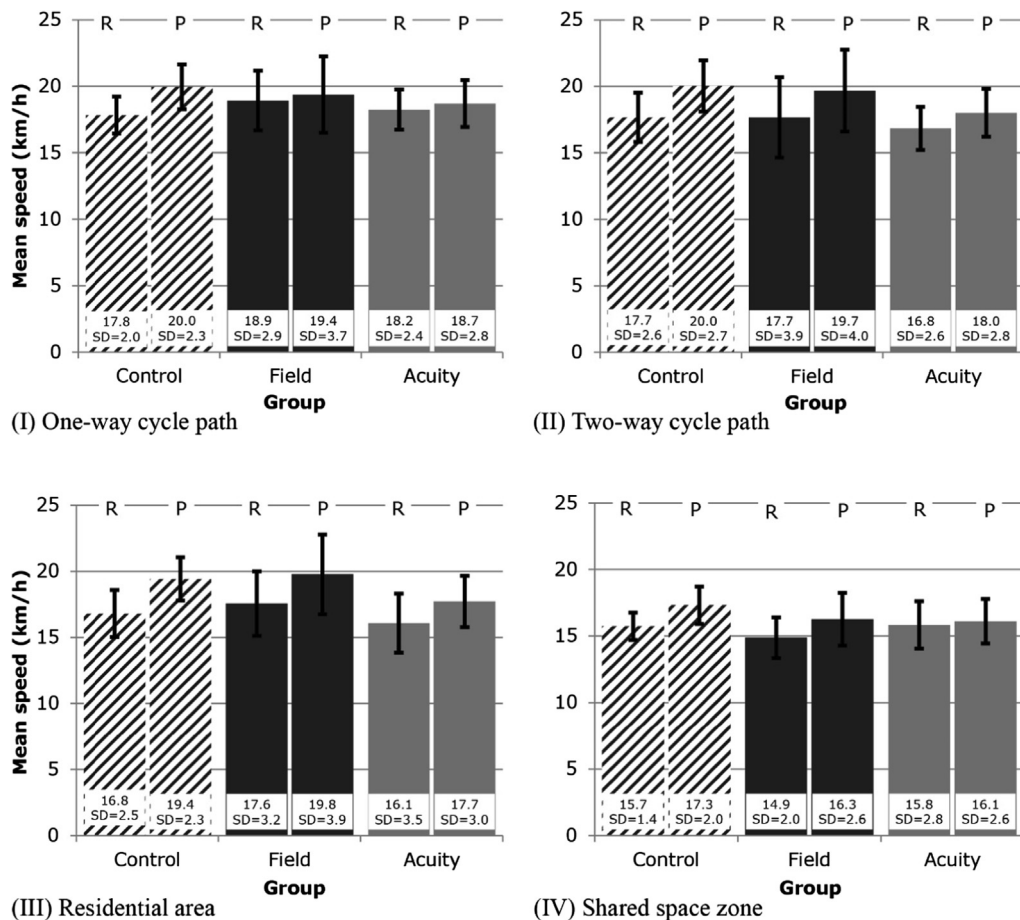
This work was supported by ZonMW, The Netherlands Organisation for Health Research and Development [Project number: 94311002; <https://www.zonmw.nl/en/>].



**Appendix A. Lane change 1 (top) and lane change 2 (bottom) from the participants' perspective. The marked traffic signs indicate a mandatory cycle path**



**Appendix B. Mean speed (km/h) on the regular bicycle (R) and the pedelec (P) per group (I) on the one-way cycle path, (II) on the two-way cycle path, (III) in the residential area, and (IV) in the shared space zone. The error bars represent the 95% confidence interval**



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